Study of critical technology items for an Advanced Earth Orbiting Atmospheric Chemistry/Climate Observatory Using Cryogenic Millimeter/Submillimeter Receivers

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Abstract- This paper is a progress report on a NASA Earth Science Technology office task for studies of critical technology items that can greatly benefit future atmospheric chemistry and climate observations from space by microwave techniques. Present Earth observing microwave instruments use room temperature or modestly cooled receivers. Future instruments could gain a factor of 30 or more in sensitivity (a factor of 900 or more reduction in required measurement time) by cooling a few key components to 4 and 20 Kelvin. We are studying concepts that can enable a mm/submm wavelength instrument with the receiver front-end mixers and amplifiers cooled to 4 and 20 Kelvin respectively by cryocoolers that appear feasible and affordable. There is, potentially, a substantial savings in cryocooler development cost by coordinating with developments now underway by NASA Code S. We have developing a thermal/mechanical concept that should limit the cryocooler power consumption to 160 watts or less for a complement of three sideband-separating radiometers. In addition, to take advantage of the decrease in required integration time, we have developed a novel, deployable, azimuth-scanning antenna system that can provide twice-daily (day and night) full global coverage of microwave observations for atmospheric chemistry and climate from an instrument in low Earth orbit.

I. Introduction

It is well recognized that 'human activity is now powerful enough to begin to affect our planet' [1]. A prime example is anthropogenic effects on stratospheric chemistry that lead to global depletion of our protective ozone layer and the Antarctic ozone hole [e.g., 2]. Tropospheric ozone and related trace gases have also been perturbed significantly and are likely to have modified the atmospheric oxidizing capacity (affecting the ability of air to 'cleanse itself') and contributed to climate change [e.g., 3, 4]. Anthropogenic effects on climate due to greenhouse gas increases [e.g., 5] are also, of course, a very important - but very difficult to quantify - global change issue.

Microwave remote sensing of Earth's atmosphere [e.g., 6, 7] is an important method of obtaining global observations needed for atmospheric chemistry and climate. Microwave measurements are obtained from observations of atmospheric spectral line thermal emission, allowing daily global coverage from a satellite-based instrument. Additional important features include the ability to (1) make chemical measurements in the presence of dense volcanic aerosol, smoke, and ice cloud, and (2) measure signals from weak spectral lines in the presence of nearby very strong ones. These features are due to (1) the relatively long wavelengths - compared to infrared, visible, and ultraviolet spectral regions - and (2) the excellent spectral resolution available from heterodyne techniques.

These techniques have already been developed and applied to stratospheric chemistry measurements from space. The Microwave Limb Sounder (MLS) experiments [8] on the Upper Atmosphere Research Satellite (UARS), launched in 1991, and the EOS Aura mission to be launched in 2004, have stratospheric chemistry measurements as a primary goal - particularly measurements needed for understanding chemistry influencing delicate balances maintaining the ozone layer and the effect of anthropogenic chlorine on ozone depletion. Important results from UARS MLS include the first global mapping of ozone destroying ClO [9], for which microwave techniques provide a unique capability. Upper tropospheric water vapor, which influences how greenhouse gas and sea surface temperature variations affect climate, has also been measured by UARS MLS [10] which provides unique daily coverage and measurements in the presence of ice clouds. More than 200 peer-reviewed MLS-related scientific publications have been produced to date; a listing is available at http://mls.jpl.nasa.gov. The second-generation MLS on EOS Aura will measure many additional stratospheric chemicals that can be globally observed only by microwave techniques. EOS MLS is also designed to provide improved measurements of upper tropospheric water vapor and other parameters that are needed for climate research studies.

Although microwave techniques have reached a relatively high degree of maturity for application to *stratospheric* chemistry, and have been applied to climate research, they have not yet been developed for *tropospheric* chemistry. Recently, however, some microwave measurements relevant to tropospheric chemistry processes and pollution been obtained from UARS MLS data, and give an example of unique measurements that this technique can provide for tropospheric chemistry. Methyl cyanide (CH_3CN), a pollutant product of biomass burning, has been detected in the UARS MLS data, which have provided its first global stratospheric climatology [11]. A localized enhancement of methyl cyanide in the lower stratosphere has also been detected and traced to an Idaho forest fire [12]. An important thrust of the work whose progress is being reported here is to identify cost-effective technology developments that can enable the full potential of the microwave remote sensing technique to be applied to tropospheric chemistry. Because of absorption by water

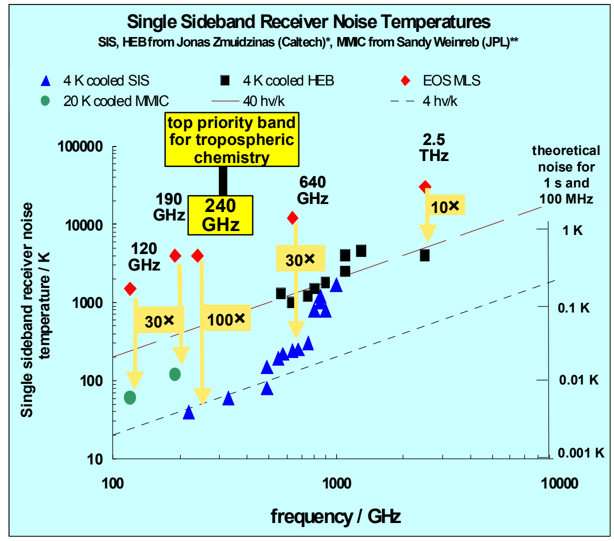

Fig. 1. Noise of a current mm/submm chemistry sensor operating at ambient temperature (EOS MLS, to be launched in 2004) compared with what now can be expected using advanced technology cooled components. Adapted from [13], with points added for EOS MLS and 20 K cooled MMIC projections. MMIC is "microwave monolithic integrated circuit," SIS is "superconductor-insulator-superconductor," and HEB is "hot electron bolometer."

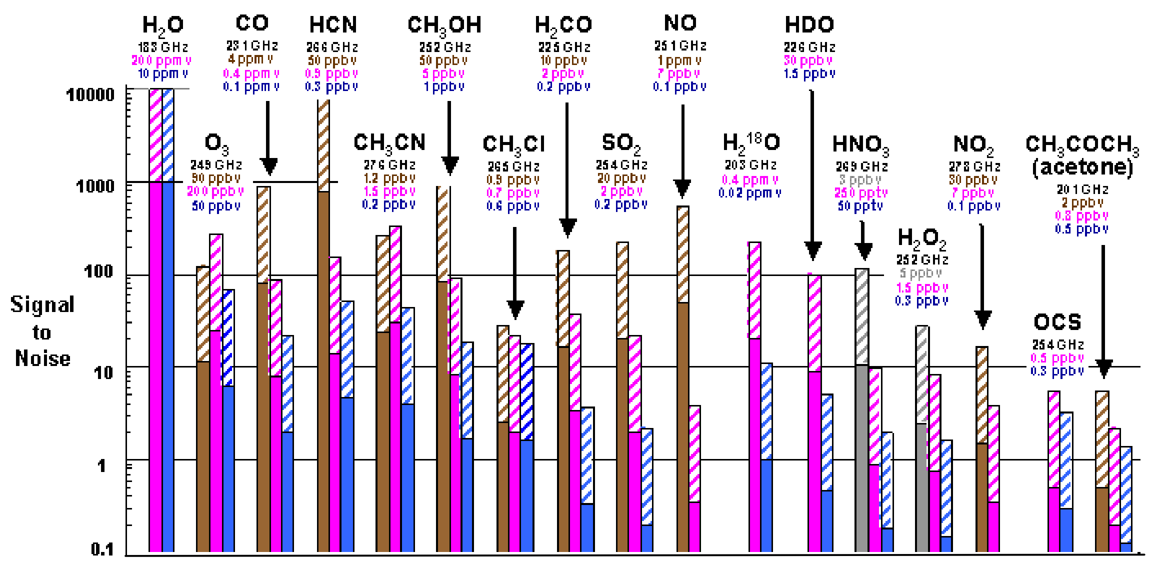

Fig. 2: Some of the candidate molecules and spectral lines for mid-upper tropospheric chemistry measurements by a future satellite-based sensor with T_{sys} = 100 Kelvin. Legend:

solid: 'reasonably confident' - 0.1 K radiance uncertainty = ~ noise for ~0.01 s integration
striped: 'realistic goal' - 0.01 K radiance uncertainty = ~ noise for ~1 s integration
blue: for typical or minimum UT abundances
pink: for enhanced UT abundances that have been observed or inferred
brown: for boundary layer enhanced abundances that can be convectively transported directly to the UT
grey: for boundary layer enhanced abundances of soluble species that may reach UT less easily

Values shown here are expected for ~9 km height at midlatitudes; ~3 x better at 11 km (nearer tropopause) vapor, these techniques - at least from space - are expected to be limited to the middle and upper troposphere (above ~5 km) [7], important regions for understanding coupling between regional and global phenomena, coupling between chemistry and climate, and coupling between the troposphere and stratosphere

II. Approach and some general considerations

Our approach is to identify technical developments that likely can have the greatest impact on atmospheric measurements, especially those needed for tropospheric chemistry measurements, for NASA missions launching ~2010-2015. This launch time period is sufficiently near for meaningful planning, while sufficiently distant to provide time for developments that can have substantial benefits.

General areas have been identified that (a) can provide substantial benefit for future chemistry/climate missions, (b) are timely for starting development, and (c) are likely to be affordable. These include:

(1) significant improvements in radiometric sensitivity needed for tropospheric chemistry measurements,

(2) significant improvements in microwave limb sounding spatial resolution needed for both chemistry and climate, and

(3) programmable measurement capability needed for a cost-effective instrument with flexible measurements.

These areas involve developments, mainly, at the component or subsystem level. System-level considerations must also be addressed and in order for the benefits of these developments to be realized in practice. These include insuring (or having methods for 'calibrating out' deficiencies) adequate radiometric stability and overall linearity for allowing measurement of the weak tropospheric spectral line superimposed on a strong continuum.

III. Radiometric Sensitivity Improvements

Figure 1 compares current satellite-based radiometric sensitivity at millimeter and submillimeter wavelengths, as available on EOS MLS for launch in 2004, with sensitivity that can be expected with advanced technology that could be deployed in future missions. Note that a factor of thirty or more improvement is expected, which gives *a three order of magnitude reduction in the required integration time.* Fig. 2 shows the resulting signal to noise with which, in principle, some important middle and upper tropospheric chemistry measurements can be made assuming a 100 K receiver and 0.01 and 1.0 second integration times. Note that many measurements, at least for polluted situations (generally the situations of most interest), can be achieved - in principle - with measurement times of a small fraction of a second. The improvements in sensitivity that are now possible can thus enable the application of microwave remote sensing to the measurement of tropospheric chemistry. However, cooling is needed and - in addition to the required technology developments - the overall instrument into which the technology is to be infused must be affordable. Cooling by stored cryogen is not feasible because of the large mass of cryogen required and the desired operational lifetime for Earth observation missions. The Cryogenic Limb Array Etalon Spectrometer CLAES [14] flown on UARS, for example, needed ~1000 kg of neon/CO_2 cryogen for cooling to 10 K with an operational lifetime of only 1.5 years. A 4 K mechanical refrigerator being developed by Sumitomo (for the 600 GHz SubMIllimeter wave Limb Emission Sounder (SMILES) to be deployed on the Japanese Experimental Module of the International Space Station) is estimated to require ~200 W for cooling to ~4.3 K, with an overall SMILES power consumption of ~900 W [15, 16]. A goal of our work is to identify methods/technology by which the power required for cooling a more ambitious instrument is ~200 W or less, with an overall instrument power consumption of three to five hundred Watts.

IV. A 'STRAWMAN' INSTRUMENT CONCEPT

In order to determine overall drivers on an advanced mm/submm atmospheric sensor, and how - overall - to make such an instrument affordable, we have developed a 'strawman' instrument concept that is providing a framework

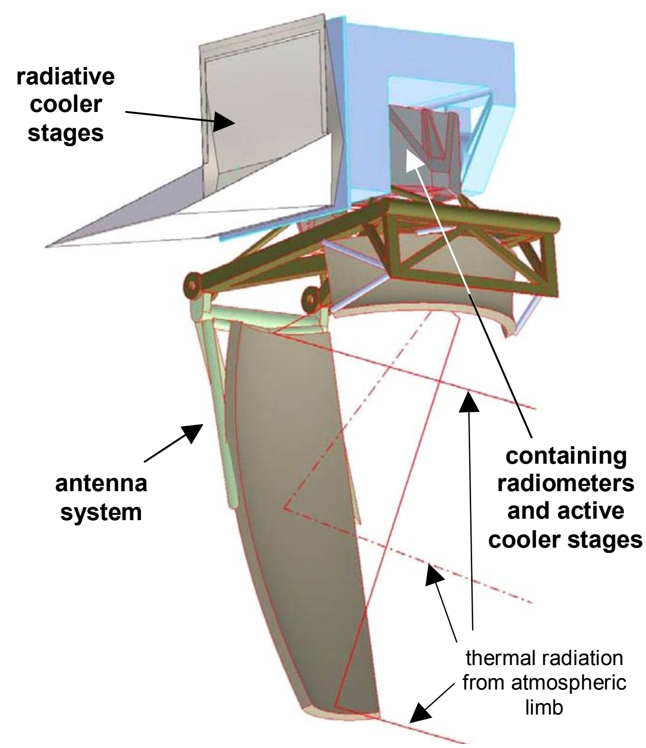

Fig. 3. An advanced microwave instrument concept for atmospheric chemistry and climate measurements.

for understanding how new technologies and capabilities might best be deployed in a practical instrument. This approach is needed in order to identify the technologies that can have a 'home' in an overall instrument that is feasible.

The ~3 km or better vertical resolution needed for measurements, and the need to measure very weak signals from trace gases, requires limb observations. Fig. 4 shows the 'strawman' instrument signal flow block diagram. We have selected the following, as optimum spectral bands and technology, to provide the needed measurements:

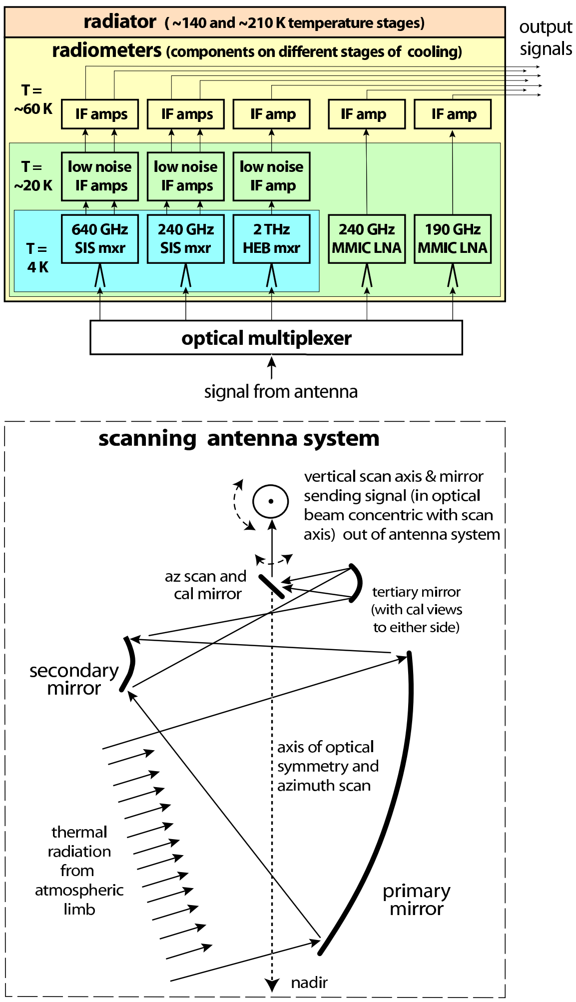

Fig. 4. Signal flow block diagram of a 'strawman' instrument concept. The different colors in the top portion refer to different stages of cooling for various components of the radiometer systems. The scanning antenna system collects radiation from the atmospheric limb and measures a vertical profile by vertically-scanning the entire antenna system over ~1° angular range - covering the altitude range of interest. A small (few cm diameter) 'azimuth scanning and calibration' mirror, located near a focal point, performs azimuth scanning for complete orbit-to-orbit coverage, as shown in Fig. 5, and radiometric calibration. A complete vertical scan is done in ~25 s, each azimuth scan and calibration in ~0.5 s, and individual measurements in ~0.02 s. The 'output signals' indicated here go to further amplifiers, band splitters, spectrometers, and a data collection system.

- 180-280 GHz ('240 GHz') SIS sideband separating radiometer with programmable measurement capability, primarily for tropospheric chemistry observations,
- 240 GHz MMIC radiometer, primarily for temperature and pressure (from 234 GHz $O^{18}O$ line) that have strong signals and need to be measured continuously,
- 190-GHz MMIC radiometer, primarily for H_2O with a strong signal that needs to be measured continuously
- 600-680 GHz ('640 GHz') SIS radiometer with programmable measurement capability, primarily for stratospheric chemistry,
- 2.0-2.5 THz ('2 THz') HEB radiometer for programmable stratospheric chemistry measurements that cannot be obtained at the lower frequencies.

All spectral bands contribute to measurement of ice cloud parameters important for climate research. The design is modular so that decisions on each band can be made at appropriate times in mission formulation and development.

V. OPTICS AND SCANNING PATTERN

A novel, and relatively simple, antenna concept has been generated that provides simultaneous vertical and 'azimuth' scanning. This concept, an outgrowth of a rotating radiometer/feed antenna developed many years ago [17] for another application, gives simultaneous scanning and

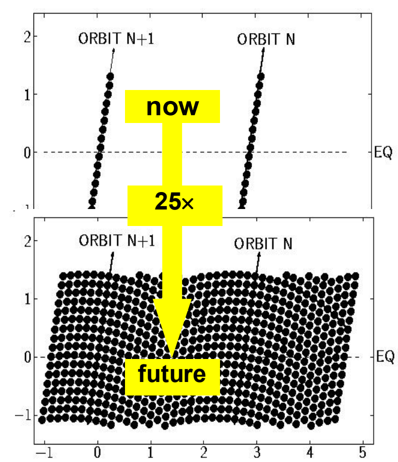

Fig. 5. The improvement in microwave limb sounding cross-track resolution enabled by the new scanning antenna concept combined with the sensitivity of cooled radiometers. This improvement in resolution will help understand regional-global couplings in the atmosphere and upper tropospheric processes important to climate variability. Each bullet gives the location of a vertical profile measurement. Coverage near the equator (EQ) from two adjacent orbits is shown here. Distances are in 1000 km units.

calibration of all spectral bands. It also greatly reduces the overall power consumption of a previous instrument concept that gave azimuth coverage by an array of MMIC-based radiometers (which could not be used at higher frequencies of interest). The azimuth scanning is conical about the limb, so that each azimuth scan covers - approximately - the same tangent point height. Fig. 5 shows the great improvement in cross-track resolution enabled by this capability.

Fig. 3 shows an initial overall concept for the advanced instrument. This concept accommodates cooled radiometers, a hybrid active-passing cooling system to reduce power consumption, and azimuth scanning for complete orbit-to-orbit coverage. Vertical resolution is set by the size of the primary mirror. A primary mirror 'vertical' dimension of ~1.6 m (seen from the direction of the atmospheric limb) as flown on UARS and EOS MLS provides 2-3 km vertical resolution for most measurements. Improving the vertical resolution to 1-2 km is desirable, but requires a larger primary mirror. A deployable antenna utilizing new technology such as the precision rotary joint and latching mechanism developed by the NASA Langley Research Center for the Next Generation Space Telescope (NGST) could allow an instrument with such a high resolution antenna to fit within present launch vehicles. Figure 6 shows a concept for a 4 meter antenna incorporated in a Delta 2 fairing.

VI. Mechanical/thermal model

We developed a thermal/mechanical model (shown in fig.7) to test the viability of the proposed instrument with the set of receivers described above. For present, we are assuming redundant coolers roughly based on designs proposed by for 6 Kelvin coolers through the Advanced Cryocooler Technology Development Program (ACTDP). The instrument consists of nested 4, 20, 60, 140, and 210 K stages with radiation barriers between all but the 4 and 20 K stage. The 4, 20, and 60 K stages are actively cooled while the 140 and 210 K stages are passively coupled to radiators.

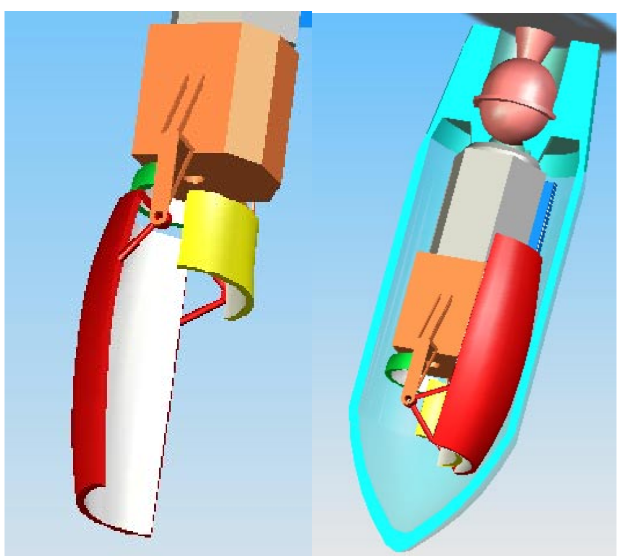

Figure 6. Deployment scheme for 4 meter aperture. Using a single hinge mechanism, an instrument with a 4 meter can be accommodated in a Delta 2 fairing. The primary, secondary, and tertiary are red yellow and green respectively. The orange structure houses the cryostat and the radiometers. The gray structure is the spacecraft bus.

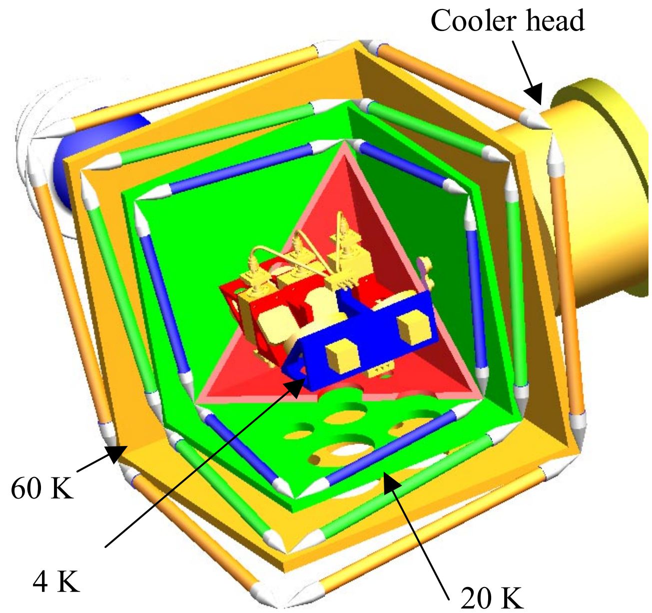

Fig.7: Cryostat concept: Shown above are cutaway views of the 4, 20, and 60 Kelvin stages of the proposed cryostat. Three sides of the 20 (green) and 60 Kelvin (gold) radiation barriers are removed. Each cube is supported off of the outer one by 3 bipods. The radiation barrier is an integral part of the mechanical structure.

Each stage is suspended on 3 bipods from the next highest temperature stage. Depending on the stage temperature, the bipods are constructed from thin walled fiberglass, alumina, or graphite tubes. To reduce thermal loading, these bipods are designed to run the longest available straight path between each stage, giving them lengths from 13 cm to 33 cm. A generous 750 grams was assumed for the 4 Kelvin receivers and focusing optics. The dominant mass in the cryogenic system at present is the thermal barriers constructed from aluminum isogrid (see fig.9). A mechanical analysis of this concept was performed giving a first vibrational mode at 140 Hz, which is deemed adequate for most launch scenarios.

To reduce thermal loading on the 4 Kelvin stage, the 190 and 240 GHz receiver front ends are mounted on the 20 Kelvin stage as are the low noise IF amplifiers for the SIS and HEB mixers. The signals and local oscillators for the mixers are coupled in quasi-optically. A small amount of DC current is dissipated on the 4 K stage in the magnetic coils associated with the SIS mixers. Otherwise, the

heat load item	cryocooler heat load (mW)			required drive power per item (Watts)	required bus power @ 89% efficiency (Watts)
	4K stage	20 K stage	60K stage		
structure, radiative load	0.8	1.4	216	13	15
structure, conductive load	**2.0**	**20**	**80**	**21**	**24**
redundant cooler	4.4	52	173	50	56
190 GHz MMIC radiometer	0	12	163	12	13
240 GHz MMIC radiometer	0	12	136	10	12
240 GHz SIS radiometer	**2.3**	**21**	**72**	**23**	**26**
640 GHz SIS radiometer	2.1	21	34	20	23
2 THz HEB radiometer	0.8	11	18	9	10
TOTAL	**12 mW**	**150 mW**	**900 mW**	**160 W**	**180 W**
specific power for each stage	5000	400	40		
drive power per stage (Watts)	**60 W**	**60 W**	**36 W**		
drive power for all stages (Watts)	160 W				
Required bus power with 5 W tare and 89% power supply efficiency	**185 W**				

Fig.8: Estimated thermal each of each of the stages from each of the receivers.

Mass Summary (grams)						
Item	4 K stage	20-60 K Stage	60-140 K Stage	140-210 K stage	210-300 K Stage	Sum
Bipod	38	123	110	226	356	853
Thermal Barrier	N/a	468	1036	1752	2853	6109
Fitting	N/a	71	112	124	135	442
System	749	718	272	12	37	1788
Sum	787	1380	1530	2114	3381	**9192**

Fig.9: Mass distribution of structural, thermal, and electrical components of cryogenic portion of the "straw man" instrument. Note that the dominant mass is the isogrid radiation shielding.

dominant heat loads on the 4 K stage are due to conduction losses through the five IF cables (2 each for the sideband splitting 240 and 640 GHz receivers and one for the HEB), the mechanical support structure, radiative loading, and the redundant cryocooler. The contribution for each is tabulated in fig. 8 along with the loads on the 20 and 60 K stages. We assume a 5000, 400, and 40 specific power for the 4, 20, and 60 K stages giving a total DC power requirement from the spacecraft for cooling the instrument of less than 200 watts. We expect this to be in line with future earth science missions. Valuable science could be still be obtained with less power by eliminating the redundant cooler and/or some receiver bands.

VII. AREAS FOR FURTHER STUDY AND DEVELOPMENT

The following have been identified as key areas for further study and/or development. Progress in these areas can have large benefits for an advanced microwave instrument for atmospheric chemistry and climate that could be operational in the ~2010-2015 time period.

A. Cooling system

Essential for microwave tropospheric chemistry measurements is a cooling system with low power consumption that can be used on Earth-orbiting satellites. This system should provide cooling to 4 K with additional stages at higher temperatures. We demonstrated that by combining active and passive (radiative) cooling, and by minimizing heat loads on the actively-cooled stages, an instrument requiring less than 200 watts for cooling can dramatically extend our present earth observing capabilities. Our studies to date indicate that actively cooled stages at 4 K, ~20 K and ~60 K - with passively cooled stages at ~140 K and ~210 K - are optimum. Developments of advanced active coolers, by the NASA Space Science Enterprise, can possibly benefit our application.

B. SIS Technology

SIS-based receivers provide the lowest noise available in the 200-300 GHz region (see Fig. 1) that is optimum for tropospheric chemistry measurements (see Fig. 2). Key SIS component developments needed for tropospheric chemistry are increasing the spectral bandwidth and generating separate outputs for the mixer upper and lower sidebands. Presently JPL and Cal Tech are developing sideband separating SIS mixers with the goal of $T_{sys} < 100$ K, 6-18 GHz, and >15 dB sideband rejection over an RF frequency from 180 to 280 GHz. To reduce the load on the cooler, the first IF amplifier is located on the 20 K stage and connected via a lossy line to the 4 K mixers. The radiometer's performance and ease of manufacture would be improved by placing a modest gain (~15 dB) low noise IF amplifier on the 4 K stage. The DC power draw of the proposed amplifier would need to be less than 1 mW to fit within the present cooler concepts.

C. MMIC Technology

MMIC-based receivers can provide excellent measurements of stronger tropospheric signals (such as temperature, pressure, water vapor and certain other chemicals such as ozone and carbon monoxide) with cooling to temperatures substantially above the 4K required for SIS-based receivers. These MMIC-based receivers provide an excellent complement (for the stronger tropospheric signals) to the SIS-based receivers (for the weaker tropospheric signals). The key MMIC development needed for this application is a 240 GHz low-noise amplifier to operate at temperatures down to ~20 K. The most appropriate temperature for operation of the MMIC amplifier will be determined after further system-level trade-offs have been made.

D. High Dynamic Range Spectrometer

Tropospheric chemistry observations require measurement of ≤ 0.1 K brightness temperature spectral lines, up to 1-2 GHz wide, that are superimposed on a continuum background of ~100 K. This requires broadband spectrometers that operate with excellent differential linearity, over a large dynamic range. A promising approach, enabled by the rapid improvement of ASIC and FPGA capabilities, is digital filter-bank spectrometers. By digitizing before spectrally resolving the signal, any saturation effects are common to all filterbank channels. An additional feature is the filter can be reprogrammed depending on the line frequency and width. The key element that needs to be developed is a low power (< ~1-2 W), high speed (~5 GHz or faster sampling, ~5 GHz or broader RF bandwidth) sampler with 3+ bit resolution. Spectral resolution needed for the tropospheric measurements is ~100 MHz.

E. Scanning Antenna System

The novel scanning antenna system described here has been studied mathematically with both geometrical and physical optics models. Development and testing of a breadboard is needed to validate the mathematical models. In addition, vertical resolution is directly related to antenna size. As shown in fig. 6, a 4 meter antenna can be accommodated in a modest sized launch vehicle, however the mass of the antenna and its support structure will likely drive the maximum size. Considerable mechanical and thermal analysis is required to determine how the graphite fiber reinforced composite manufacturing approach used on EOS MLS will perform on a much larger antenna.

F. *Advanced Calibration Techniques*

Most astrophysical applications of high performance radiometers run in balance, i.e. the radiometer view is switched between the scene being studied and a reference view at close to the same temperature. This technique limits sensitivity to calibration errors and gain drift. For a satellite-based radiometer scanning the earth's atmosphere, the scene temperature can rapidly change from 3 to 300 Kelvin. For current instruments with T_{sys} of 1000 to 4000 K this is a minor issue. However, for an advanced radiometer with T_{sys}~100 K, more sophisticated calibration targets that optically combine two calibration views to generate a calibration temperature to match the scene temperature may be required.

G. Demonstration Instrument

As the sensitivity of receiver front ends improves, errors due to gain variation, system nonlinearity, and calibration errors will eventually limit the instrument's performance. To take full advantage of the improved sensitivity of cooled receivers, a test bed for demonstrating the performance of an end-to-end system is critical. This test bed can be used to test proposed components and gain stabilization techniques while demonstrating the techniques applicability to tropospheric measurements and mitigating risk for a future flight program. This could be either a balloon or a mountain top based experiment.

H. HEB technology

HEB technology provides best noise performance for microwave measurements at frequencies above ~1200 GHz (see Fig. 1), and measurement of several important stratospheric chemicals (e.g., atomic oxygen and hydroxyl radical) can only be done in this range. HEB-based radiometers require sufficiently-small local oscillator (LO) power, like SIS devices, that the LO can be generated by solid state technology - which is both more reliable and consumes less power than the 2.5 THz gas laser local oscillator used for the OH measurement on EOS MLS. HEB technology, especially in the 2.0-2.5 THz region (both the HEB devices and the solid state technology for tunable LO generation) should be developed to a sufficient level of maturity for deployment in an advanced satellite instrument for stratospheric chemistry measurements.

I. Schottky technology

Schottky-based radiometer systems have - to date - been the 'workhorse' for atmospheric chemistry measurements with microwave techniques. Advances in this technology, at least at frequencies above ~300 GHz where development of low noise MMICs is not yet feasible, should continue to be supported for applications in which cooling to the lower temperatures required for SIS and HEB is not available or needed. We are not yet at a stage in development of an advanced chemistry instrument that we can rule out the need for Schottky technology being most cost-effectively used in a portion of the instrument.

VIII. Summary

Microwave techniques have already been developed and applied with great benefit to stratospheric chemistry measurements, and are also being used for climate research. Technology developments are now possible that can allow these techniques - with their unique ability to measure through ice clouds, dense aerosol and smoke - to be applied to the important area of tropospheric chemistry. In particular, an instrument flying superconducting mixers and cryogenic amplifiers appears viable. The vast potential improvement in sensitivity can allow microwave techniques that have demonstrated success in the stratosphere to measure the troposphere with high accuracy and special resolution. The developments for tropospheric chemistry will also greatly improve stratospheric chemistry and climate research measurements by this technique.

Acknowledgements

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